

## **Multiwavelength Modeling of Nova Atmospheres Final Report—Summary of Research**

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### **Detailed NLTE Model Atmospheres for Novae during Outburst:**

#### **II. Modeling optical and ultraviolet observations of Nova LMC 1988 #1.**

*with Greg J. Schwarz, S. Starrfield, E. Baron, France Allard, Steven N. Shore, P. Whitelock*

LMC 1988 #1 was a slow, CO type, dust forming classical nova. It was the first extragalactic nova to be observed with the IUE satellite. We have successfully fitted observed ultraviolet and optical spectra of LMC 1988 #1 taken within the first two months of its outburst (when the atmosphere was still optically thick) with synthetic spectra computed using PHOENIX nova model atmospheres. The synthetic spectra reproduce most of the features seen in the spectra and provide V band magnitudes consistent with the observed light curve. The fits are improved by increasing the CNO abundances to 10 times the solar values. The bolometric luminosity of LMC 1988 #1 was approximately constant at  $2 \times 10^{38}$  ergs s<sup>-1</sup> at a distance of 47.3 kpc for the first 2 months of the outburst until the formation of the dust shell.

#### **A Non-LTE Line-Blanketed Stellar Atmosphere Model of the Early B Giant $\epsilon$ CMa**

*with J. P. Aufdenberg, S. N. Shore, E. Baron*

We successfully reproduce the full multi-wavelength spectrum, including the extreme ultraviolet (EUV) continuum observed by the *Extreme Ultraviolet Explorer*, of the B2 II star  $\epsilon$  CMa with a non-LTE fully line-blanketed spherical model atmosphere. The available spectrophotometry of  $\epsilon$  CMa from 350 Å to 25  $\mu$ m is best fit with model parameters  $T_{\text{eff}} = 21750$  K,  $\log(g) = 3.2$ , and an angular diameter of 0.77 mas. Our model predicts a hydrogen ionizing flux,  $q_0$ , of  $1.59 \times 10^{21}$  photons cm<sup>-2</sup> s<sup>-1</sup> at the star's surface and 5540 photons cm<sup>-2</sup> s<sup>-1</sup> at the surface of the Local Cloud.

Our synthetic spectra are in excellent agreement with observed continuum and line fluxes from échelle spectra obtained with the Goddard High Resolution Spectrograph. While we find agreement between the absolute UV flux of  $\epsilon$  CMa as measured by *GHR*S and our model atmosphere, these fluxes are ~30% higher in the UV than measured by *IUE*, *OAO-2*, and *TD-1*, in excess of the published errors in the absolute calibration of these data. The *IUE* and *TD-1* data appear to have a wavelength independent systematic error in their absolute calibration of 30%. The *OAO-2* data, in agreement with the model's absolute flux between 1200 Å and 2000 Å, lie 30% below the model and *GHR*S fluxes from 2000 Å to 3000 Å, suggesting a relative as well as absolute calibration error in these data.

The agreement between the model and the measured EUV flux is a result of the higher temperatures at the formation depths of the H I and He I Lyman continua compared to other models. These higher temperatures increase the level of the EUV continuum and reduce the strength of the 912 Å and

504 Å edges. An important difference between our calculations and previous calculations is the computation of the model atmosphere out to very small optical depths which results in higher temperatures in the EUV continuum forming region.

### **Spectroscopy Of Low Metallicity Giant H II Regions: A grid of low Metallicity Stellar atmospheres**

*with S.L. Pistinner, D. Eichler, & E. A. Baron*

We calculate a grid of spherically symmetric OB stellar atmospheres at low metallicities, including both non-local thermodynamic equilibrium (NLTE) and metal line blanketing effects. This is done to assess the uncertainties in helium abundance determination by nebular codes due to input stellar atmosphere models. The more sophisticated stellar atmosphere models we use can differ from LTE models by as much as 40 percent in the ratio of He to H-ionizing photons.

### **Infrared Colors at the Stellar/Substellar Boundary**

*with S.K. Leggett and F. Allard*

We present new infrared JHK photometry for 61 halo and disk stars around the stellar/substellar boundary. We also present new L' photometry for 21 of these stars and for 40 low-mass stars taken from the Leggett 1992 photometry compilation. These data are combined with available optical photometry and astrometric data to produce color-color and absolute magnitude-color diagrams — the current sample extends the similar work presented in the 1992 paper into more metal-poor and lower mass regimes. The disk and halo sequences are compared to the predictions of the latest model atmospheres and structural models.

We find good agreement between observation and theory except for known problems in the V and H passbands probably due to incomplete molecular data for TiO, metal hydrides and H<sub>2</sub>O. The metal-poor M subdwarfs are well matched by the models as oxide opacity sources are less important in this case. The known extreme M subdwarfs have metallicities about one-hundredth solar, and the coolest subdwarfs have  $T_{eff} \sim 3000$  K with masses  $\sim 0.09 M/M_{\odot}$ . The grainless models are not able to reproduce the flux distributions of disk objects with  $T_{eff} < 2500$  K, however a preliminary version of the NextGen-Dusty models which includes homogeneous formation and extinction by dust grains is able to match the colors of these very cool objects. The least luminous objects in this sample are GD165B, three DENIS objects — DBD0205, DBD1058 and DBD1228 — and Kelu-1. These have  $T_{eff} \sim 2000$  K and are at or below the stellar limit with masses  $\leq 0.075 M/M_{\odot}$ . Photometry alone cannot constrain these parameters further as the age is unknown, but published lithium detections for two of these objects (Kelu-1 and DBD1228) imply that they are young (aged about 1 Gyr) and substellar (mass  $\leq 0.06 M/M_{\odot}$ ).

### **On the abundance of Lithium in T CrB**

*with T. Shahbaz, and T. Naylor*

We have obtained high resolution echelle spectroscopy of the recurrent nova T CrB. We compare the surface abundance of Li in T CrB with field M-stars and find it to be somewhat below solar, whereas in the M3iii field stars it is non-existent. We offer possible explanations for this in terms of either a delay in the onset of convection in the giant star, enhanced coronal activity due to star-spots or the enhancement of Li resulting from the nova explosion.

**Numerical Solution of the Expanding Stellar Atmosphere Problem**  
*with E. Baron*

In this paper we discuss numerical methods and algorithms for the solution of NLTE stellar atmosphere problems involving expanding atmospheres, e.g., found in novae, supernovae and stellar winds. We show how a scheme of nested iterations can be used to reduce the high dimension of the problem to a number of problems with smaller dimensions. As examples of these sub-problems, we discuss the numerical solution of the radiative transfer equation for relativistically expanding media with spherical symmetry, the solution of the multi-level non-LTE statistical equilibrium problem for extremely large model atoms, and our temperature correction procedure. Although modern iteration schemes are very efficient, parallel algorithms are essential in making large scale calculations feasible, therefore we discuss some parallelization schemes that we have developed.

**The NextGen Model Atmosphere grid for  $3000 \leq T_{\text{eff}} \leq 10000$  K**  
*with F. Allard and E. Baron*

We present our NextGen Model Atmosphere grid for low mass stars to effective temperatures larger than 3000 K. These LTE models are calculated with the same basic model assumptions and input physics as the VLMS part of the NextGen grid so that the complete grid can be used, e.g., for consistent stellar evolution calculations and for internally consistent analysis of cool star spectra. This grid is also the starting point for a large grid of detailed NLTE model atmospheres for dwarfs and giants (Hauschildt et al, in preparation). The models were calculated from 3000 K to 10000 K (in steps of 200 K) for  $3.5 \leq \log g \leq 5.5$  (in steps of 0.5) and metallicities of  $-4.0 \leq [M/H] \leq 0.0$ .

We discuss the results of the model calculations and compare our results to the Kurucz 1994 grid. Some comparisons to standard stars like Vega and the Sun are presented and compared with detailed NLTE calculations.

**Period-luminosity, -color, and -radius relationships of Cepheids as a function of metallicity: Evolutionary effects.**

*with Yann Alibert, Isabelle Baraffe and France Allard*

Based on consistent evolutionary and pulsation calculations, we analyze the effect of metallicity and different convection treatment in stellar models on P-L, P-C and P-R relationships. In order to perform accurate comparison with observations, we have computed grids of atmosphere models and synthetic spectra for different metallicities, covering the range of effective temperatures and gravities relevant for this study. The models are compared to recent observations of galactic and Magellanic Cloud Cepheids. In general, good agreement is found between models and observations.

We show that for the range of metallicities of the Galaxy and the Magellanic Clouds a change of slope in the P-L relationship is predicted at low periods due to the reduction of the size of the blue loop during core He burning. The minimum mass undergoing a blue loop and consequently the critical period at which this change of slope occurs depends on the metallicity  $Z$  and the convection treatment in the stellar models. The variation of this minimum mass with metallicity yields a dependence of  $Z$  on the P-L relationship which is a consequence of evolutionary effects.

### **Barnes-Evans relations for late-type giants and dwarfs**

*with K. Beuermann and Isabelle Baraffe*

The visual surface brightness of giants and young disk dwarfs differ slightly, in agreement with recent theoretical models. We present improved Barnes-Evans type relations for late-type giants and dwarfs and simple fit formulae which allow to estimate dwarf radii.

### **The multiple system LHS 1070: a case study for the onset of dustformation in the atmospheres of very low mass stars** *with Christoph Leinert, France Allard, Andrea Richichi*

LHS 1070 (other common name: GJ 2005) is a nearby multiple system consisting of very low mass red dwarfs. We present the results of WFPC2 photometry and FOS spectroscopy for the three optically resolved components of this system acquired during HST cycle 5. These show (1) absolute brightnesses corresponding to theoretical masses of 0.078- 0.083  $M_{\odot}$  and 0.076-0.081  $M_{\odot}$  for the faint pair, depending mainly on their age and metallicity; (2) a saturation of the optical TiO and VO absorption bands typical of the onset of photospheric dust formation, and (3) emission lines typical of moderate chromospheric activity in only the two most massive components. Li I lines are not seen. But also all other lines of the alkali elements are remarkably weak or even absent in the two faint companions B and C. This appears to be an effect of dust formation. Comparison of the observations with model spectra, which account for dust formation and for the resulting opacities, yields good agreement for solar metallicity and effective temperatures and gravities (in  $\log \text{cm/s}^2$ ) of 2950 K;5.3, 2400 K;5.5 and 2300 K;5.5 for the three components A,B and C, respectively. The existence of a fourth component, recently discovered in this system by HST Fine Guidance Sensor observations (Henry et al. 1999), has already been taken into account in the evaluation of the data for the main component. An effective temperature and gravity (in  $\log \text{cm/s}^2$ ) for the fourth component of 2500 K;5.3 would best be compatible with our data. Then, based on our analysis the three components C, B and D of LHS 1070, in this order, are the faintest stars within 20 pc of the Sun for which dynamical determinations of mass appear possible within a decade. The system LHS 1070 thus has the potential to be the most important source of information for probing the low mass end of the main sequence.

### **Spectral Energy Distributions for Disk and Halo M-Dwarfs** *with S.K. Leggett, F. Allard, Conard Dahn, T.H. Kerr, J. Rayner*

We have obtained infrared (1–2.5 micron) spectroscopy for 42 halo and disk dwarfs with spectral type M1 to M6.5. These data are compared to synthetic spectra generated by the latest model atmospheres of Allard & Hauschildt. Photospheric parameters metallicity, effective temperature and radius are determined for the sample.

We find good agreement between observation and theory except for known problems due to incomplete molecular data for metal hydrides and H<sub>2</sub>O. The metal-poor M subdwarfs are well matched by the models as oxide opacity sources are less important in this case. The derived effective temperatures for the sample range from 3600 K to 2600 K; at these temperatures grain formation and extinction are not significant in the photosphere. The derived metallicities range from solar to one-tenth solar. The radii and effective temperatures derived agree well with recent models of low mass stars.

**An Effective Temperature Scale for Late M and L Dwarfs, from Resonance Absorption Lines of Cs I and Rb I** with *Gibor Basri, Subhanjoy Mohanty, France Allard, Xavier Delfosse, Eduardo L. Martin, Thierry Forveille, Bertrand Goldman*

We present Keck HIRES spectra of 6 late-M dwarfs and 11 L dwarfs. Our goal is to assign effective temperatures to the objects using detailed atmospheric models and fine analysis of the alkali resonance absorption lines of Cs I and Rb I. These yield mutually consistent results when we use “cleared-dust” models, which account for the removal of refractory species from the molecular states but do not include dust opacities. We find a tendency for the Rb I line to imply a slightly higher temperature, which we ascribe to an incomplete treatment of the overlying molecular opacities. This work, in combination with results from the infrared, hints that dust in these atmospheres has settled out of the high atmosphere but is present in the deep photosphere. We also derive radial and rotational velocities for all the objects, finding that the previously discovered trend of rapid rotation for very low mass objects is quite pervasive. To improve on our analysis, there is a clear need for better molecular line lists and a more detailed understanding of dust formation and dynamics.

**A Non-LTE line-blanketed expanding atmosphere model for A-supergiant  $\alpha$  Cygni** with *J. P. Aufdenberg, E. Baron*

We present non-LTE metal line-blanketed expanding atmosphere models and synthetic spectra for comparison with the spectral energy distribution of A-supergiant  $\alpha$  Cyg from the UV to the radio. Our model treats the hydrostatic inner atmosphere and the extended expanding outer atmosphere as a unified structure and the radiative transfer is computed in the co-moving frame. By simultaneously fitting the UV, optical, IR and radio spectrophotometry we constrain  $\dot{M}$ . Stability of the deep hydrostatic layers against outward acceleration demands that the gravitational potential at the photosphere be  $\log g \approx 1.5$ . The best fitting model angular diameter is in very good agreement with the most recent interferometric measurement. We find a good fit to the photospheric Balmer and Pfund lines. We fit the Mg II resonance lines and find a best fit terminal velocity of  $v_\infty = 225 \text{ km/s}$ . We present synthetic radio spectra from the partially ionized winds of A-supergiants over a range of mass-loss rates and we find the standard assumptions regarding the radio spectra of warm supergiants break down for A-supergiants.

**non-LTE model atmosphere analysis  
of the early ultraviolet spectra of nova Andromedae 1986**  
with *Greg J. Schwarz, S. Starrfield,  
E. Baron, France Allard, Steven N. Shore, and G. Sonneborn*

We have analyzed the early optically thick ultraviolet spectra of Nova OS And 1986 using a grid of spherically symmetric, non-LTE, line-blanketed, expanding model atmospheres and synthetic spectra with the following set of parameters:  $5,000 \leq T_{\text{model}} \leq 60,000 \text{ K}$ , solar abundances,  $\rho \propto r^{-3}$ ,  $v_{\text{max}} = 2000 \text{ km s}^{-1}$ ,  $L = 6 \times 10^4 L_\odot$ , and a statistical or microturbulent velocity of  $50 \text{ km s}^{-1}$ . We used the synthetic spectra to estimate the model parameters corresponding to the observed *IUE* spectra. The fits to the observations were then iteratively improved by changing the parameters of the model atmospheres, in particular  $T_{\text{model}}$  and the abundances, to arrive at the best fits to the optically thick pseudo-continuum and the features found in the *IUE* spectra.

The *IUE* spectra show two different optically thick subphases. The earliest spectra, taken a few days after maximum optical light, show a pseudo-continuum created by overlapping absorption lines. The later observations, taken approximately 3 weeks after maximum light, show the simultaneous presence of allowed, semi-forbidden, and forbidden lines in the observed spectra.

Analysis of these phases indicate that OS And 86 had solar metallicities except for Mg which showed evidence of being underabundant by as much as a factor of 10. We determine a distance of 5.1 kpc to OS And 86 and derive a peak bolometric luminosity of  $\sim 5 \times 10^4 L_{\odot}$ . The computed nova parameters provide insights into the physics of the early outburst and explain the spectra seen by *IUE*. Lastly, we find evidence in the later observations for large non-LTE effects of Fe II which, when included, lead to much better agreement with the observations.

## **Parallel Implementation of the PHOENIX Generalized Stellar Atmosphere Program**

### **II. Wavelength parallelization**

*with E. Baron*

We describe an important addition to the parallel implementation of our generalized stellar atmosphere and NLTE radiative transfer computer program PHOENIX. In a previous paper in this series we described parallel algorithms we have developed for radiative transfer, spectral line opacity, and NLTE opacity and rate calculations. These algorithms divided the work spatially or by spectral lines, that is distributing the radial zones, individual spectral lines, or characteristic rays among different processors. For finite, monotonic velocity fields, the radiative transfer equation is an initial value problem in wavelength, and hence each wavelength point depends upon the previous one. However, for sophisticated NLTE models of both static and moving atmospheres needed to accurately describe, e.g., novae and supernovae, the number of wavelength points is very large (200,000–300,000) and hence parallelization over wavelength can lead both to considerable speedup in calculation time and the ability to make use of the aggregate memory available on massively parallel supercomputers. Here, we describe an implementation of a pipelined design for the wavelength parallelization of PHOENIX, where the data from the processor working on a previous wavelength point is sent to the processor working on the succeeding wavelength point as soon as it is known. Our implementation uses a MIMD design based on a relatively small number of MPI library calls and is fully portable between serial and parallel computers.

## **The Relative Contributions to the Near-Infrared Emission in Short Period Cataclysmic Variables**

*with David R. Ciardi and Steve B. Howell*

We present phase-resolved near-infrared broadband photometry of four short period cataclysmic variables (HU Aqr, WZ Sge, TY Psc, & V592 Cas). Coupled with ultraviolet and optical data obtained from the literature, we have modeled the spectral energy distributions of these four cataclysmic variables, as well as, the twin of WZ Sge, AL Com. The secondary stars contribute no more than 20–50% of the near-infrared flux except for the polar HU Aqr where the secondary contributes  $\sim 75\%$  of the near-infrared flux. For the systems located above the orbital period minimum, the temperatures of the secondary stars match those for the expected main sequence secondary stars. However, our modeling places WZ Sge below the orbital period minimum and containing a secondary star of  $< 1700$  K – the coldest star yet identified.

## **Observations of the Polar ST Leonis Minoris During an Extreme Low State: Identification of the Secondary Star**

*with David R. Ciardi, Steve B. Howell, V. S. Dhillon, R. Mark Wagner, and F. Allard*

We present near-infrared and optical spectroscopic observations of the polar ST Leonis Minoris (ST LMi) in an extreme low-state. The near-infrared spectrum, showing no emission lines whatsoever, is produced solely by the secondary star. We have fit the spectrum with a series of stellar atmosphere models and found the secondary star to have a temperature of  $2800 \pm 200$  K. Six months later, ST LMi was reobserved in the near-infrared, at which time mass transfer had resumed, and the system was now in a high state. We find evidence to suggest that the second pole in ST LMi was actively accreting material.

## **PAHs & Grains in Carbon-rich Stellar Atmospheres**

*with Jason W. Ferguson, David R. Alexander, Hollis R. Johnson & France Allard*

Comparison of laboratory spectra of PAHs with observed spectra from the interstellar medium, H II regions, and carbon-rich circumstellar shells of planetary nebulae indicate the presence of PAHs in these objects. In fact, several investigators have estimated that a large fraction of interstellar carbon is bound in PAHs and similar complex molecules. If so, one is faced with identifying a source and production mechanism, and those presently remain obscure. An obvious location for their production would be the atmospheres or winds of giant carbon stars. Unfortunately, results of calculations to the present show extremely low abundances of these molecules in all but a small region of the pressure – temperature plane. In this paper we extend previous calculations to include the presence of carbon-bearing grains as well as many more molecules in the EOS and simultaneously extend the calculations over a larger region of the pressure – temperature plane. Our results disclose a sensitive interplay between PAHs and carbon-bearing grains. Grains and PAHs form at very nearly the same values of temperature and density, and grains preferentially lock up all the carbon atoms. Our results clearly demonstrate that PAHs cannot form in equilibrium, and we suggest some alternatives.

**List of Publications in refereed journals (1996–2001)**  
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